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New Physical Models and Methods for Source Localization

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**13. ABSTRACT (Maximum 200 words)**

The research focuses on the development of sensor processing methods for source localization and parameter estimation. The main contributions are: the introduction of electromagnetic and acoustic vector-sensor processing; development of radar polarimetric methods, including remote sensing applications, and optimum choices of transmitting signals and polarizations; methods for sensor calibration using active sources; localizing sources using a samll number of mobile sensors that can replace methods with a large number of stationary sensors; localization of vapor emitting sources with chemical sensor arrays; detection of radioactive sources with projection-based sensor arrays; localization of current dipoles with SQUID magnetic sensors.

The methods have been analyzed using performance bounds, statistical techniques, and computer simulations. Several fundamental results have been established on source parameter identifiability, such as expressions for the maximum number of sources identifiable in array processing models. Other results include techniques for quantifying and tracking non-rigid object motion and for spectral line filtering. Transition of the acoustic work has been made to the Naval ASTO Office and NUWC Lab. Potential transitions to civilian applications include seismology, biomedicine, and environmental sensing.

**14. SUBJECT TERMS**

source localization, physical models, sensor array processing, polarimetry, remote sensing, SAR, vector sensors, radioactive, vapor, dipole sources identifiability, signal processing, estimation.

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# Final Report
# Research Under Grant F49620-93-1-0096
# February 1, 1993 to August 31, 1996

## Objective:

The main objective of this research was to develop methods for source localization and parameter estimation using array processing, whereby data is collected at multiple sensors and then fused to carry out the estimation task (space-time processing). Such methods have to be statistically accurate and computationally fast. For performance analysis, there is a need to develop quality measures and optimum bounds. To obtain significant performance improvement, it is useful to look at the problem from a systems perspective. This is done, for example, by employing novel sensors and demonstrating the improvement using performance analysis, computer simulation, and later hardware prototypes. In this way signal processing becomes a powerful tool that influences the design of a system as a whole, and is not limited to data processing. Our work is primarily applicable to military problems such as radar and sonar, but has dual-use in civilian applications such as seismology, biomedicine, environment, and astronomy wherever possible.

## Status, Accomplishments, and New Findings:

Our original work on vector-sensor processing for locating and estimating the polarization state of electromagnetic sources will appear as a book chapter in [1]. (Electromagnetic vector sensors measure the complete electric and magnetic fields at a single point in space). An array of such vector sensors measures direction information in both the wave structure and the time delays between the sensors. We derived a compact expression of the Cramér-Rao bound for vector-sensor arrays and sources with multiple parameters and signals. We proposed new quality measures for direction and orientation estimation in 3D space, including mean-square angular error and covariance of vector angular error, and derived lower bounds on them. These results are of general interest and are not limited to EM waves. We used them to show that a vector-sensor array has great advantages over its traditional scalar-sensor array counterpart due to the information in the wave structure: With one vector sensor it is possible to find the direction and polarization ellipse of up to three sources (see below); A

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vector sensor can resolve closely spaced sources based on polarization sensitivity. Thus, we determined that with one vector sensor it is possible to do what historically was done by an array of distributed traditional sensors. We also proposed a fast, robust, real-time direction estimation algorithm for a wide-band source using a single vector sensor and analyzed its performance. A patent was awarded for this algorithm.

The idea of using vector sensors challenges our thinking about notions of "antenna aperture", since here it is clear that one can indeed perform source location with sensors of arbitrarily small dimension (subject only to a limitation on the amount of energy which can be received).

In [2] and [3] we developed models for radar polarimetric methods, including remote sensing. (Polarimetry is the process of analyzing the properties of a surface that is reflecting or emitting an electromagnetic wave by examining the wave's polarization). Our work involved creating and parametrizing statistically accurate polarimetric models. We obtained lower bounds on the error of estimating an object's polarimetric signature, and used them to provide efficient choices of parametrizations and transmitting signals. The work is expected to have use in repeat-track and ultra-wideband synthetic aperture radar (SAR).

In [4] and [5] we developed calibration methods for sensor position estimation using active source signals, which reduces the source parameter estimation error compared with conventional methods that use only passive sources. We derived the Cramér-Rao bound for this problem and used it to find the optimal arrangement of source signals for sensor calibration.

In [6] we analyzed optimal beamspace vector-sensor array processing methods, where use was made of dimensionally reduced data vectors. The optimality here was with respect to the best possible element space parameter estimation accuracy given by the Cramér-Rao bound.

In [7], [8] we introduced methods for localizing sources using mobile sensors. The sensors' movements are selected to minimize the localization error. The main advantages of these methods are: 1) A single moving sensor can accomplish the task of a large array of stationary sensors, by exploiting spatial and temporal diversity; 2) The sensor motion can be planned in real time, based on past measurements and minimization of the expected localization error as a function of the future sensor's position, in order to optimize localization performance.

We applied the methods to vapor-emitting sources using moving chemical sensors.

In [9]–[13] we established several general results on source parameter identifiability. We found expressions for the maximum number of sources identifiable in any array processing model that has multiple parameters and signals per source. We presented a method to incorporate *a priori* information about the sources. These results are central to current research in the field and were applied to analyze the resolution of vector-sensor arrays as a function of the source properties.

In [14] we described general methods to establish identifiability and information-regularity of parameters in normal distributions. Parameters are considered identifiable when they are uniquely determined by the probability distribution and they are information-regular when their Fisher information matrix is full-rank. In normal distributions, information-regularity implies local identifiability but the converse is not always true. Using the theory of holomorphic mappings, we derived conditions under which the converse is true, allowing information-regularity to be established without having to explicitly compute the information matrix. The results can be applied to various estimation problems.

In [15]–[17] we extended the vector-sensor idea to acoustic sources, and developed localization methods that use the acoustic particle velocity and the acoustic pressure; traditional methods use only the pressure. We showed that one vector sensor can find the direction to two acoustic sources. In [15] we analyzed the statistical performance of two simple algorithms for estimating the source direction with a single acoustic vector sensor. In [16] we considered beamforming and Capon direction of arrival (DOA) estimation using arrays of acoustic vector sensors. We derived an expression for the Cramér-Rao bound (CRB) on the DOA parameters of a single source. Using this, we gave conditions that minimize the lower bound on the asymptotic mean-square angular error, and conditions that ensure it is isotropic. We were also able to determine the signal-to-noise ratio (SNR) and geomtry conditions for which the use of vector sensors is most advantageous. The asymptotic performance of the Capon and beamforming estimators was analyzed and compared with a scalar-sensor array. The vector-sensor array was seen to have improved performance due to its elements' directional sensitivity. In particular, we showed that no ambiguities can arise, which permits the use

of deliberately undersampled arrays that can attain a smaller estimation error with fewer sensors. Large sample approximations for the mean-square error (MSE) matrices of the estimators were derived. Throughout, we compared vector-sensor arrays with their scalar-sensor counterparts.

In [17] we considered acoustic vector-sensor arrays mounted on or near a boundary. We showed that hull-mounted sonar arrays are usable at low frequency if normal-component veloctiy sensors are employed (at such low frequencies the pressure signal is negligible due to the nature of the hull's reflective properties). After developing a general model for vector-sensor arrays mounted near a plane boundary with arbitrary reflective properties, we obtained an expression for the CRB on the location parameters for a single source. Using this expression, we compared the normal-component array with a "stand-off" pressure sensor array mounted some distance from the hull and developed the notion of *critical stand-off distance*, which is the minimum stand-off distance required of the pressure-sensor array for comparable performance. The results are also applicable to floating arrays or in room acoustics. Transition of the acoustic work has been made to the Naval ASTO Office and NUWAC Lab (see also below).

In several instances we were able to find civilian applications of our techniques. These were explored in a number of papers. In [18] and [19], we extended our results on localizing electromagnetic polarized sources to seismic sources. We presented a model for polarized seismic waves measured by three-component geophone receivers, and parametrized by the ellipticity and orientation of the polarization ellipse. We analyzed the identifiability of the model and derived lower bounds on the mean-square angular error for source direction finding in a solid medium.

In [20] we designed techniques for localizing underground objects and identifying their parameters by measuring the components of the gravity gradient tensor. A maximum likelihood procedure was used to solve the parameter estimation problem. The Cramér-Rao bound was computed for the range and mass of a spheroidal object.

In [21] and [22] (see also [7] and [8]) we introduced methods for detecting and localizing vapor-emitting sources using chemical-sensor arrays. We described the pertinent physical models,

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developed estimation and detection algorithms, and derived relevant performance bounds. Potential applications of these methods include detecting explosives or drugs, sensing leakage of hazardous chemicals or pollutants, and environmental studies.

In [23] we developed methods for localizing radioactive and weak light sources using detector arrays that exploit the directional sensitivity of the sensors' surfaces. We considered several array shapes, developed an algorithm for direction finding, and computed its mean-square angular error. Potential applications of the proposed methods include verifying compliance with nuclear nonproliferation treaties, localizing sources of radioactive leakage, and environmental sensing. We are now developing methods for detecting and localizing nuclear activities on the ground using detector arrays onboard airplanes.

In [24] and [25] we designed methods for localizing current dipoles using arrays of magnetic sensors. We developed schemes for optimizing sensor configurations and applied the results to magnetoencephalography (MEG). Conventional MEG methods use arrays of radial magnetic sensors placed around the skull to locate current sources (dipoles) inside the brain. We provided a framework for analyzing the accuracy of a magnetic sensor array that estimates the location and direction of a dipole. We used this framework to devise arrays of non-radial sensors whose orientations are chosen to minimize location errors. We also developed a computationally efficient localization algorithm using magnetic vector sensors.

In [26]–[28] we developed a technique for quantifying non-rigid object motion from a sequence of deformable bounding surfaces. We devised algorithms that estimate flow-vector fields and describe the motion by tracking point trajectories of contour pairs. The fields were found by matching shape properties, using the physical equivalent of bending energy. We applied it to temporal analysis of left ventricular endocardial wall motion using data from magnetic resonance (MR) imaging. Experimental results for contours derived from actual cardiac MR images were presented.

In [29] we analyzed the performance of several adaptive algorithms for tracking time-varying sinewave. These find applicability in Doppler estimation or FM demodulation, for example.

**Personnel Supported:**

Faculty: Arye Nehorai. Ph.D. Students: Bertrand Hochwald and Malcolm Hawkes. Visiting Scholar: Professor Carlos Muravchik from the University of La Plata, Argentina

**Interactions/Transitions:**

Interactions: Participations at meetings and conferences are mentioned in the references below.

Transitions: Our idea of acoustic vector-sensor processing [15]–[17], [30], [31] is now being pursued by the NAVY ASTO (advanced systems and technology) office and NUWC. Our results are applied to locate sources with high accuracy using a small-size acoustic sensor array. ASTO has recently transitioned the research from category 6.1 to categories 6.2, 6.3 and 6.4. It has also created a working group of people from academia and industry to further develop and investigate the use of the new concept for hull-mounted sensors. Within this group, researchers at NUWC in New London are already conducting experiments to confirm the analytical results. The ASTO project is headed by Commander John Polcari and Mr. Mike Traweek [PEO(USW) ASTO G-4, Undersea Warfare, telephone: (703) 604-6013 ext. 527] and the NUWC project by Dr. Ben Cray [NUWC, New London, telephone (203) 440-5355].

**Patent Disclosures:**

None.

**Honors/awards:**

- IEEE Fellow, since 1994, Nehorai, A.

- SPIE Honorable Mention Award in the Best Paper Competition, for "Analysis of Cardiac Motion with Recursive Comb Filtering," in SPIE Annual Meeting on Mathematical Methods in Medical Imaging, 1994, Nehorai, A., McEachen, J. C. and Duncan, J. S.

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